QCD for the LHC

“Three simple ideas that shook the (QCD) world”

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the myths on QCD

- QCD is not cool (=old, well understood, boring)
- QCD is not useful (aren't we all interested in New Physics?)
- QCD is difficult (=only hard problems are left, progress is slow and only obtained through brute force calculations)
- QCD offers no room for NEW and SIMPLE ideas

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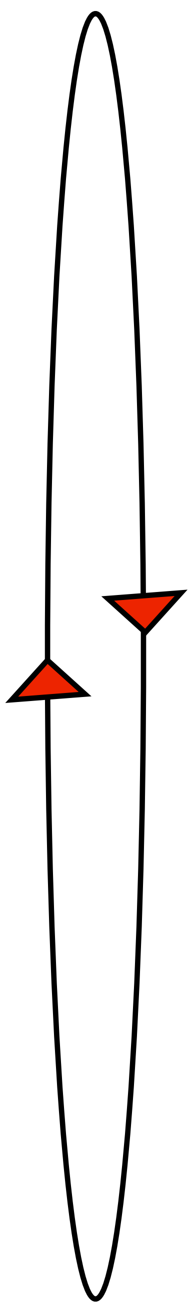
FALSE !!

Dispelling the myths on QCD

- QCD is ~~not~~ cool (string theorists now publishing on hep-ph)
- QCD is ~~not~~ useful also because we are interested in New Physics
- QCD is difficult because we ask more challenging questions
- QCD ~~no~~ room for NEW and SIMPLE ideas

LHC physics = QCD + ϵ



1. Rediscover the known SM at the LHC (top's, W's, Z's) + jets.

Accurate predictions (NLO,NNLO) for standard candles SM cross sections.

New regime for QCD will require modeling and tuning of underlying event, double parton scattering, small-x, and pdf measurement.

2. Identify Higgs or excess(es) over SM (or both!)

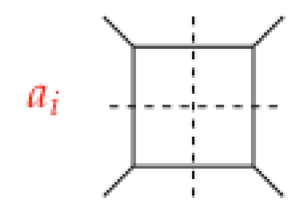
Importance of QCD depends on the nature of the physics discovered : from none (resonances) to fundamental (inclusive SUSY).
In general, fully exclusive description for rich and energetic final states with flexible MC to be validated and tuned to control samples. Shapes for multi-jet final states and normalization for key process important

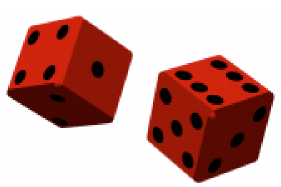
3. Identify the nature of NP by performing measurements of mass spectrum, quantum numbers, couplings.

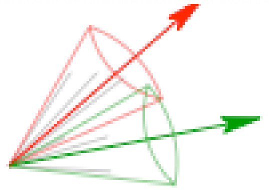
Accurate QCD predictions and MC tools for SM as well as for the NP signals.

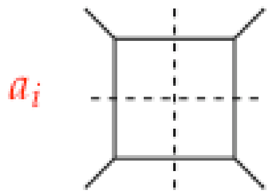
Outline

- Introduction
- Three simple ideas:
  - From trees to loops and back
  - The new Monte Carlo generation
  - The perfect jets
- Conclusions









From trees to loops and back

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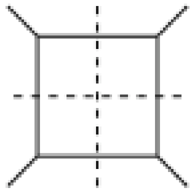


Master QCD formula

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

Two ingredients necessary:

1. Parton Distribution functions (from exp, but evolution from th).

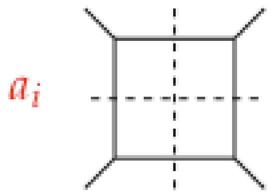
2. Short distance coefficients as an expansion in α_S (from th).

$$\hat{\sigma}_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \dots$$

Leading order

Next-to-leading order

Next-to-next-to-leading order



Leading order : Trees

* Many available algorightms for automatic generation of tree-level matrix element, some of which in a public tools:
  - -- Feynman diagrams (with tricks to reduce factorial growth) :
    CompHEP/CalcHEP, AMEGIC++, MadGraph
  - -- off-shell recursive relations: Berends-Giele, ALPHA/ALPGEN, HELAC, COMIX
  - -- on-shell recursive relations (twistor inspired) : CSW, BCFW

* Automatic/modular integration over phase space and event generation:
  - -- HELAC/PHEGAS, MadEvent, SHERPA, ALPGEN

* Merging with PS : HELAC (MLM), SHERPA (CKKW), ALPGEN (MLM), MadEvent (CKKW, KTMLM)

[Duhr, Hoeche, FM]

Final State	BG		BCF		CSW	
	CO	CD	CO	CD	CO	CD
$2g$	0.24	0.28	0.28	0.33	0.31	0.26
$3g$	0.45	0.48	0.42	0.51	0.57	0.55
$4g$	1.20	1.04	0.84	1.32	1.63	1.75
$5g$	3.78	2.69	2.59	7.26	5.95	5.96
$6g$	14.20	7.19	11.90	59.10	27.80	30.60
$7g$	58.50	23.70	73.60	646.00	146.00	195.00
$8g$	276.00	82.10	597.00	8690.00	919.00	1890.00
$9g$	1450.00	270.00	5900.00	127000.00	6310.00	29700.00
$10g$	7960.00	864.00	64000.00		48900.00	

The “good and old” BG provide the fastet approach. Need to work also for complex momenta (see later).,

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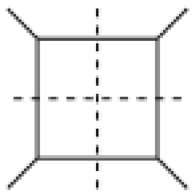
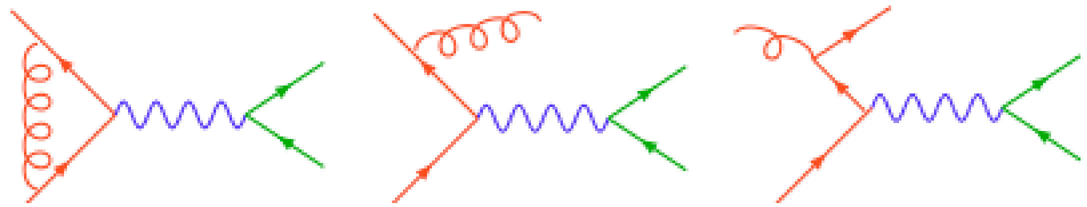


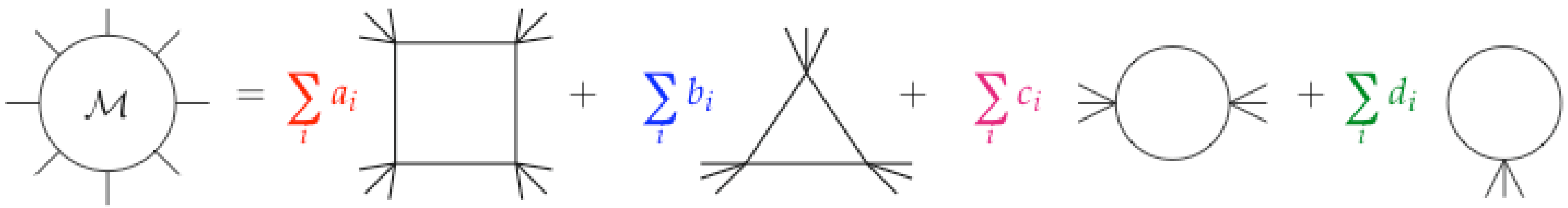
Next-to-leading order : Loops

$\hat{\sigma}^{(1)}$



virtual real

Any one-loop amplitude can be written as (PV decomposition):



$$\mathcal{M} = \sum_i a_i(D)\,\text{Boxes}_i + \sum_i b_i(D)\,\text{Triangles}_i + \sum_i c_i(D)\,\text{Bubbles}_i + \sum_i d_i(D)\,\text{Tadpoles}_i$$

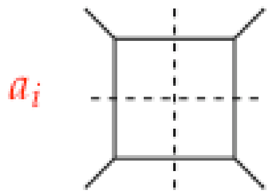
* All the scalar loop integrals are known and now easily available [Ellis, Zanderighi]

* Open issue is to compute the D-dimensional coefficient in the expansion: large number of terms forbid a direct evaluation with symbolic algebra. In addition normally large gauge cancellation, inverse Gram determinants, spurious phace-space singularities lead to numerical instabilities.

Sometimes it is better to calculate

$$\mathcal{M} = \sum_i a_i(4)\,\text{Boxes}_i + \sum_i b_i(4)\,\text{Triangles}_i + \sum_i c_i(4)\,\text{Bubbles}_i + \sum_i d_i(4)\,\text{Tadpoles}_i + R$$

Where R is a rational function

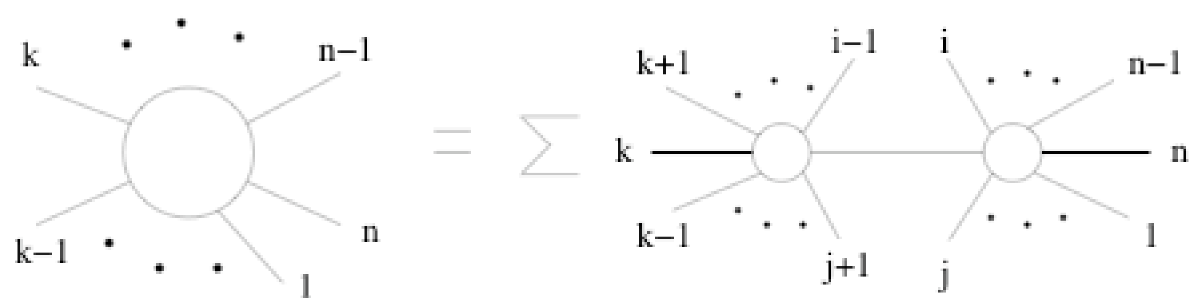


Simple idea # 1

Several new developments coming from the idea

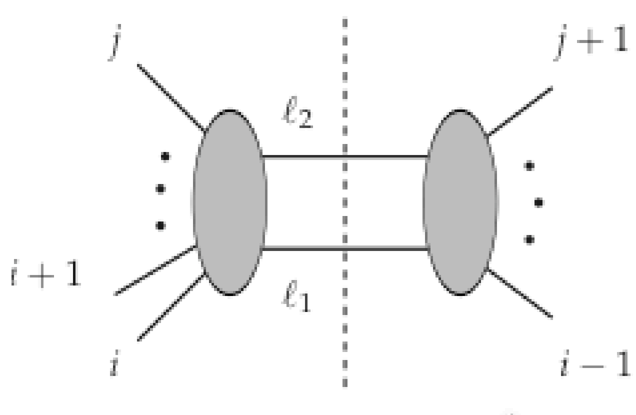
> A scattering amplitude is an analytic function of the external momenta and (most) its structure can be reconstructed from the poles and the branch cuts.
>
> LOOPS can be calculated from tree-level amplitudes

✓ POLES : lower number of external lines. Cauchy residue theorem



[Cachazo, Svreck, Witten]
[Witten]
[Britto, Cachazo, Feng]

✓ BRANCH CUTS : lower number of loops

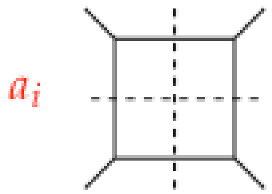


$$\text{Disc} = \int d^4\Phi\, A^{\text{tree}}(\ell_1, i, \ldots, j, \ell_2)\, A^{\text{tree}}(-\ell_2, j+1, \ldots, i-1, -\ell_1)$$

$$d^4\Phi = d^4\ell_1\, d^4\ell_2\, \delta^{(4)}(\ell_1 + \ell_2 - P_{ij})\, \delta^{(+)}(\ell_1^2)\, \delta^{(+)}(\ell_2^2)$$

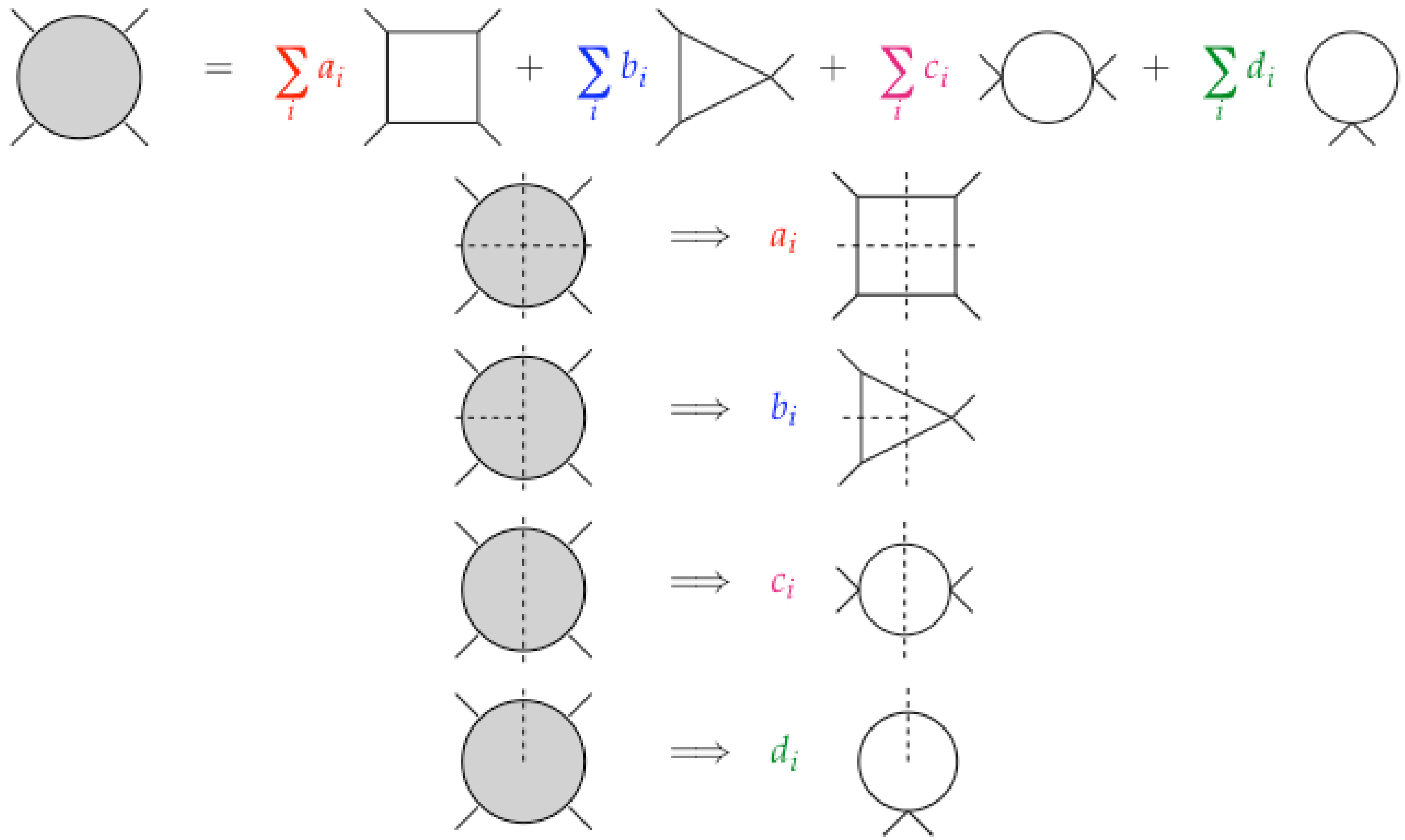
$$\delta^{(+)}(p^2) = \delta(p^2)\,\theta(p_0) \qquad \text{on-shell condition}$$

[Vermaseren, van Neerven]
[Bern, Dixon, Dunbar, Kosower]
[Britto, Cachazo, Feng]



Generalized unitarity

[Bern, Dixon, Kosower]
[Britto, Cachazo, Feng]
[Anastasiou, Kunszt, Mastrolia]



Three and four particle cuts are non zero due to the continuation of momenta into complex values!

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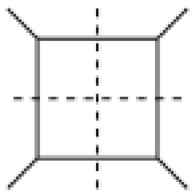
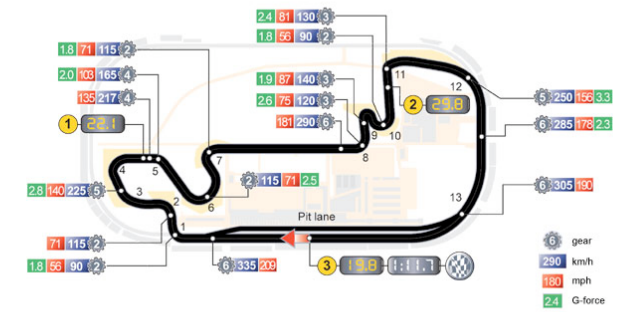


The loop race



Impressive developments in the last year(s) : automatic and multiporpose method to 1-loop calculation in sight

Unitarity-based methods

Bern, Dixon, Dunbar and Kosower
Britto, Cachazo, Feng and Witten
Bern, Dixon and Kosower
Anastasiou, Britto, Feng, Kunszt, Mastrolia
Anastasiou, Kunszt, Forde
Ossola, Papadopoulos,Pittau [CutTools]
....

On-shell recurrence relations

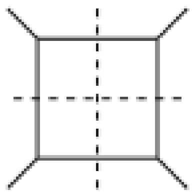
Ellis, Giele, Kunszt, Melnikov
Moretti, Piccinini, Polosa
Catani, Gleisberg, Krauss, Rodrigo, Winter
Berger, Bern, Dixon, Febres Cordero, Forde,
Ita, Kosower, Maitre [BlackHAT]
Giele, Zanderighi [Rocket]
....

Improved tensor reduction

Binoth, Guillet, Pilon, Heinrich and Schubert
Denner and Dittmaier
Xiao, Yang, and Zhu
...

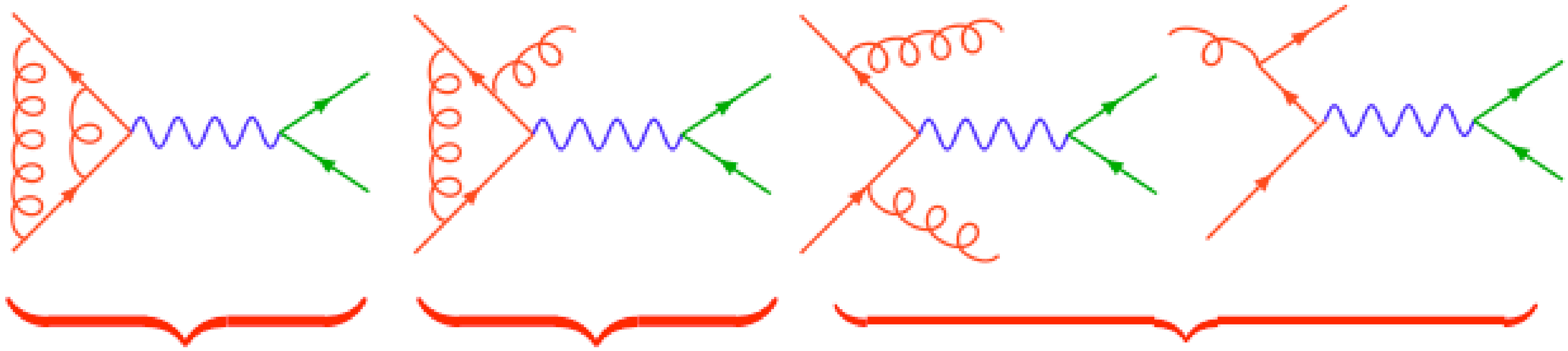
New papers and proposals on daily basis....

a_i



NNLO : status and directions

$\hat{\sigma}^{(2)}$



2 loop

1 loop +
1 extra parton

2 extra partons

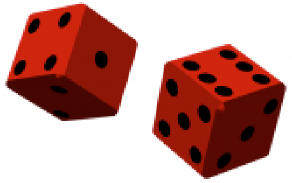
NNLO calculations provide new challenges:

* 2 loop contributions have been the bottleneck for a long time. Laporta algorithm [Laporta] and Mellin-Barnes techniques [Smirnov, Tausk] provide effective techniques.

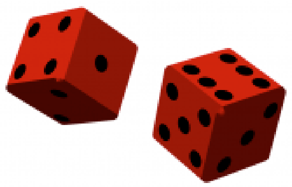
* At hadron colliders only 2→1 (singlet) procs are known at NNLO [van Neerven, Harlander, Kilgore, Anastasiou, Melnikov, Ravindram, Smith, Dixon, Petriello, Catani, Grazzini]

* Milestone achievement : e+e- → 3j at NNLO [Gehrmann-De Ridder, Gehrmann, Glover, Heinrich] providing a new extraction of α_S . Antenna's used.

* Main target : a process independent approach as universal subtraction scheme: Subtraction [Frixione, Grazzini], Dipole subtraction [Trocsanyi, Somogy, del Duca, Duhr, Aglietti] , Antenna's [Daleo, Gehrmann, Maitre]



The new Monte Carlo generation



How we (used to) make predictions?

First way:

- For low multeplicity include higher order terms in our fixed-order calculations (LO→NLO→NNLO...)
  $\Rightarrow \quad \hat{\sigma}_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \ldots$
- For high multeplicity use the tree-level results

TH

Comments:

1. The theoretical errors systematically decrease.
2. Pure theoretical point of view.
3. A lot of new techniques and universal algorithms are developed.
4. Final description only in terms of partons and calculation of IR safe observables ⇒ not directly useful for simulations

How we (used to) make predictions?

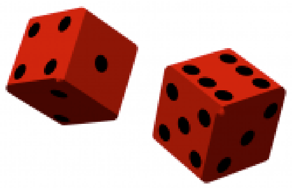
Second way:

- Describe final states with high multiplicities starting from $2 \to 1$ or $2 \to 2$ procs, using parton showers, and then an hadronization model.

EXP

Comments:

1. Fully exclusive final state description for detector simulations
2. Normalization is very uncertain
3. Very crude kinematic distributions for multi-parton final states
4. Improvements are only at the model level.



Simple idea # 2

[Mangano]
[Catani, Krauss, Kuhn, Webber]
[Frixione, Nason, Webber]

ME

1. parton-level description
2. fixed order calculation
3. quantum interference exact
4. valid when partons are hard and well separated
5. needed for multi-jet description

Shower MC

1. hadron-level description
2. resums large logs
3. quantum interference through angular ordering
4. valid when partons are collinear and/or soft
5. nedeed for realistic studies

Approaches are complementary: merge them!

Difficulty: avoid double counting

How to improve our predictions?

New trend: TH & EXP

Match fixed-order calculations and parton showers to obtain the most accurate predictions in a detector simulation friendly way!

Two directions:

1. Get fully exclusive description of many parton events correct at LO (LL) in all the phase space. ME+PS

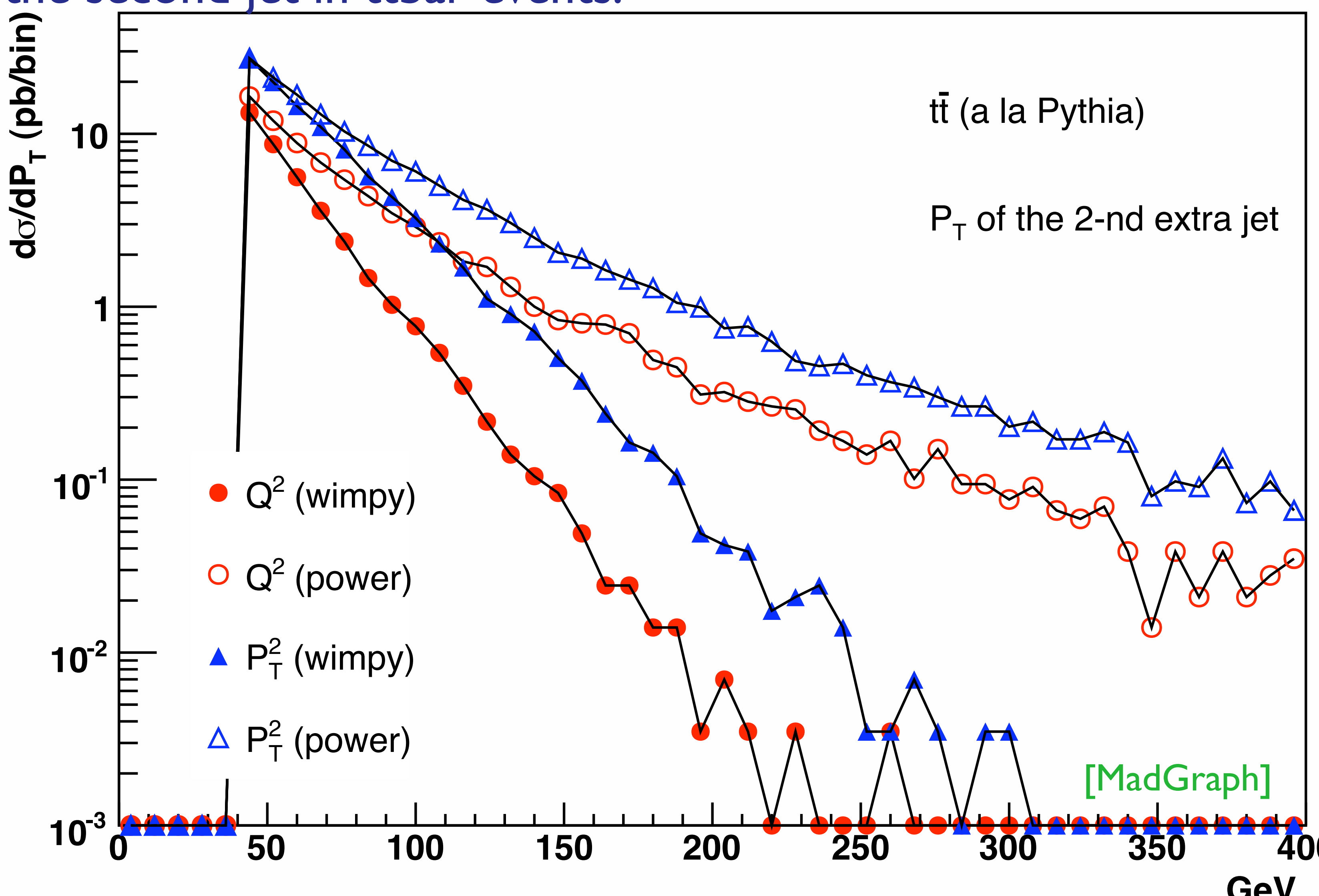
2. Get fully exclusive description of events correct at NLO in the normalization and distributions. NLOwPS

Example: the MLM matching algorithm

- Generate events with the ME, using hard partonic cut, e.g., pT>pTmin, ΔRjj > ΔRMIN, (Alpgen) or with a k_T algorithm (MadEvent).
- Reweight the event to optimize scale choices.
- Shower the event and jet-cluster it (with the same algorithm).
- Require the original partons to be one-to-one associated to the jets.

PS alone vs matched samples

A MC Shower like Pythia produces inclusive samples covering all phase space. However, there are regions of the phase space (ex. high pt tails) which cannot be described well by the log enhanced (shower) terms in the QCD expansion and lead to ambiguities. Consider for instance the high-pt distribution of the second jet in ttbar events:



Changing some choices/parameters leads to huge differences ⇒ self diagnosis. Trying to tune the log terms to make up for it is not a good idea ⇒ mess up other regions/shapes, process dependence.

PS alone vs matched samples

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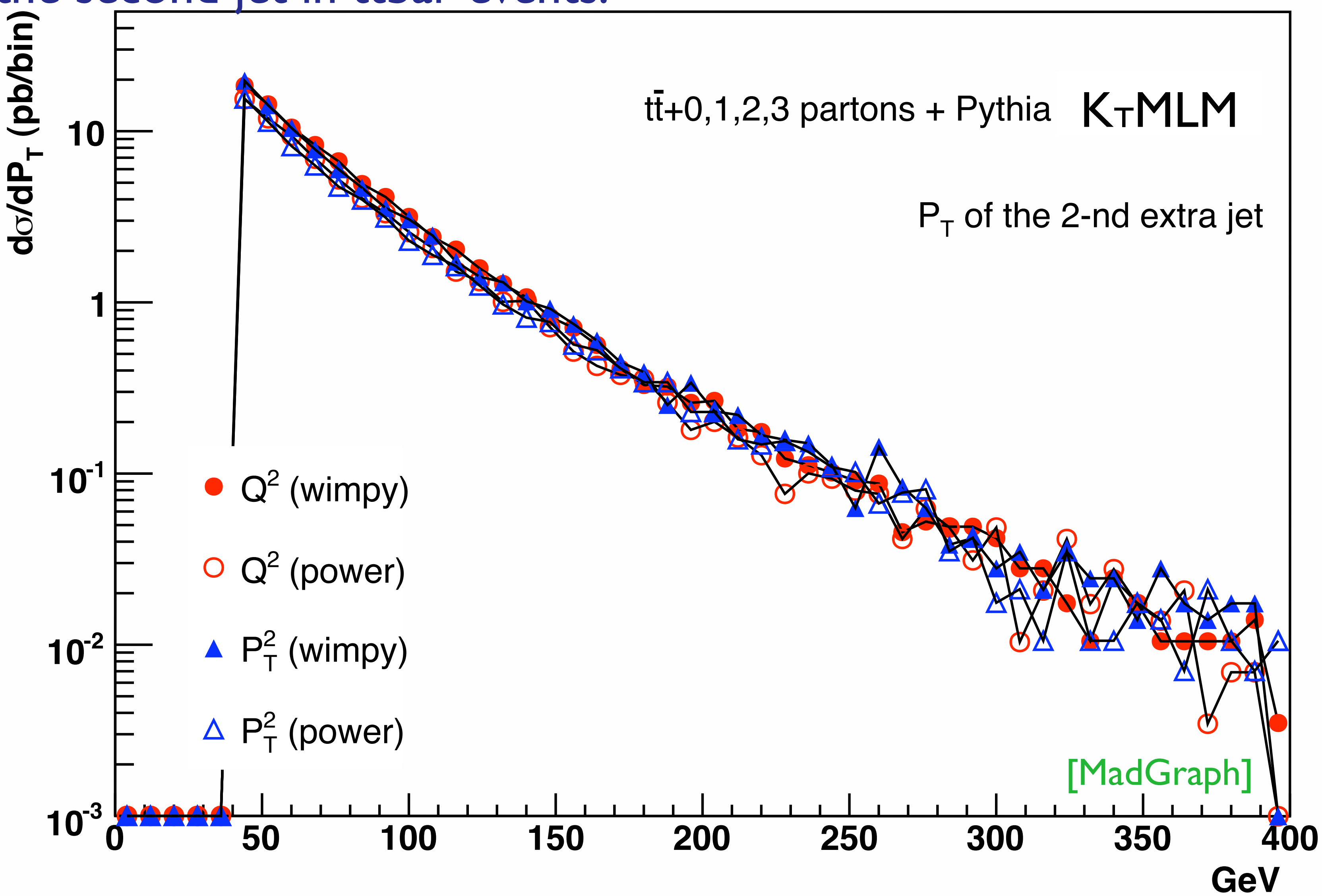
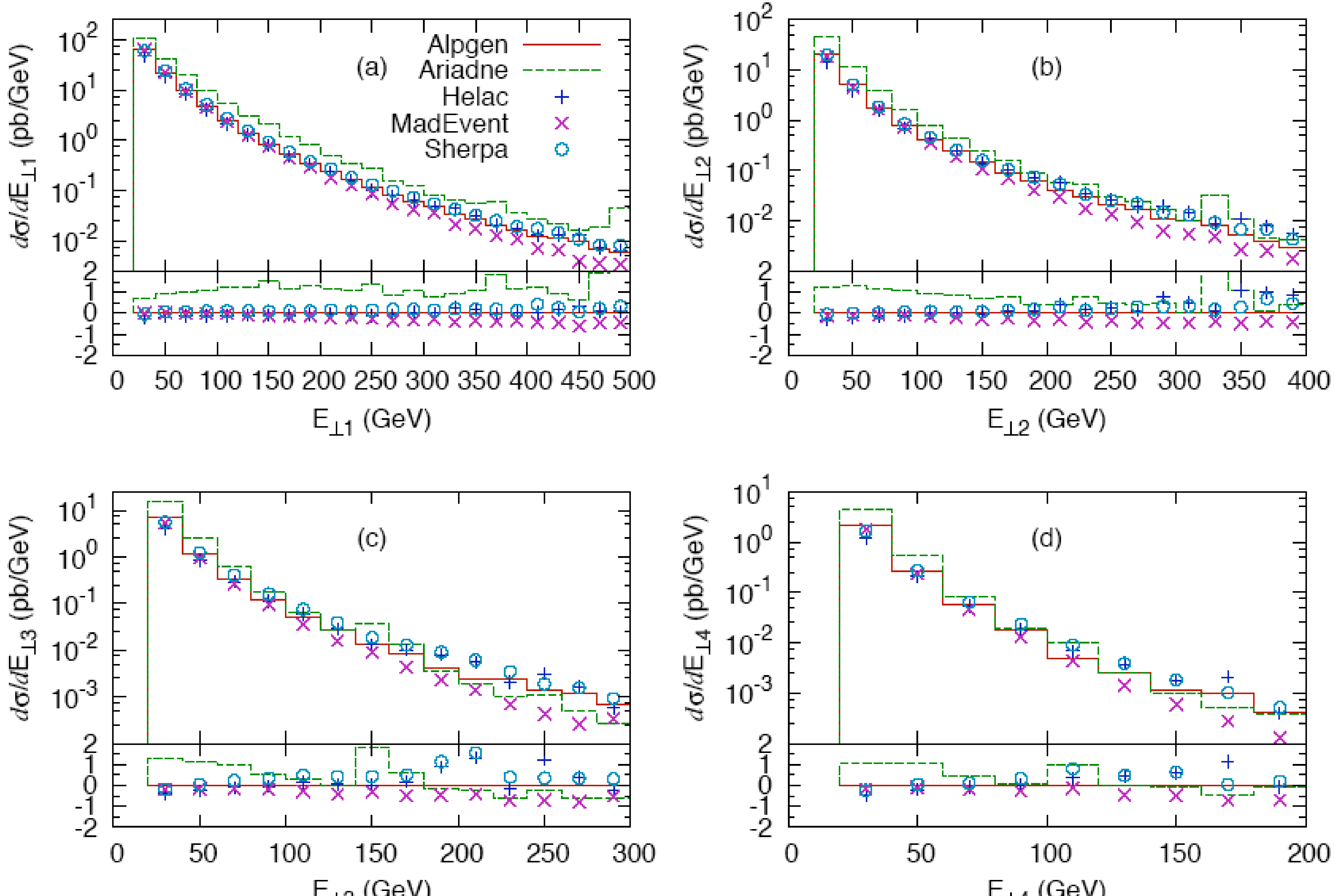


In a matched sample these differences are irrelevant since the behaviour at high pt is dominated by the matrix element. LO+LL is more reliable. (Matching uncertaintes not shown.)

W+ jets: first comparison

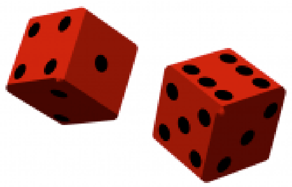
$W^{\pm}$ + jets comparison plots: Jet E_T for LHC

[J. Alwall et al., arXiv:0706.2569]



ME-PS matching in a nutshell

- It provides an algorithm to generate multi-jet inclusive samples, that are accurate in all the areas of the phase space avoiding double-counting.
- The matching (à la CKKW) has been rigorously proved in e+e- collisions and it is believed to be true also in pp collisions. The MLM matching is problematic in e+e- and just a prescription in pp, where, however, seems to work really well.
- At this stage there is a fair amount of tuning/checking/validation to make it work and evaluation of the systematics is still subject study.
- Since no exact virtual contributions are included the normalization of the cross section for each jet multiplicity is formally LO and therefore uncertain. Normalization has to be obtained from a NLO calculation.
- On the other hand, shapes and often jet rates are (so far) in very good agreement with NLO.
- Fast progress : new studies/proposals/developments every day...



NLOwPS

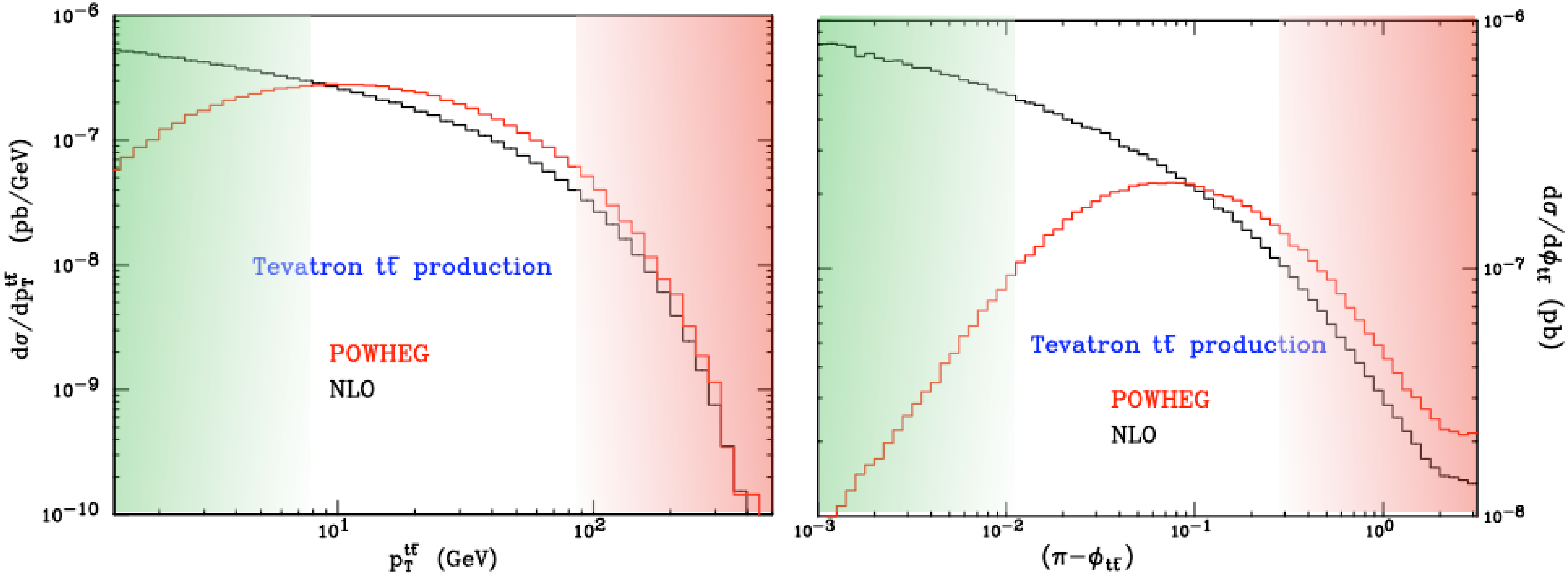
Problem of double counting becomes even more severe at NLO
* Real emission from NLO and PS has to be counted once
* Virtual contributions in the NLO and Sudakov should not overlap

Current available (and working) solutions:

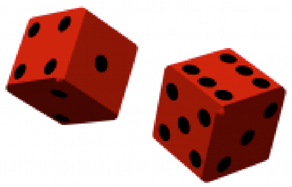
MC@NLO [Frixione, Webber, 2003; Frixione, Nason, Webber, 2003]
- Matches NLO to HERWIG angular-ordered PS.
- "Some" work to interface an NLO calculation to HERWIG. Uses only FKS subtraction scheme.
- Some events have negative weights.
- Sizable library of procs now.

POWHEG [Nason 2004; Frixione, Nason, Oleari, 2007]
- Is independent from the PS. It can be interfaced to PYTHIA or HERWIG.
- Can use existing NLO results.
- Generates only positive unit weights.
- For top only ttbar (with spin correlations) is available so far.

ttbar : NLOwPS vs NLO



* Soft/Collinear resummation of the $p_T(tt) \to 0$ region.
* At high $p_T(tt)$ it approaches the tt+parton (tree-level) result.
* When $\Phi(tt) \to 0$ ($\Phi(tt) \to \pi$) the emitted radiation is hard (soft).
* Normalization is FIXED and non trivial!!



NLOwPS

"Best" tools when NLO calculation is available (i.e. low jet multiplicity).

* Main points:
  * NLOwPS provide a consistent to include K-factors into MC's
  * Scale dependence is meaningful
  * Allows a correct estimates of the PDF errors.
  * Non-trivial dynamics beyond LO included for the first time.

N.B. : The above is true for observables which are at NLO to start with!!!

* Current limitations:
  * Considerable manual work for the implementation of a new process.
  * Only SM.
  * Only available for low multiplicity.

LO and NLO w PS : outlook

Several directions of improvement:

* Automatization at NLO

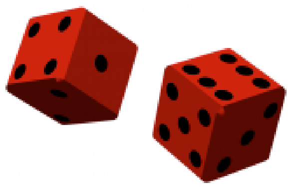
-- for the real contributions proven feasible [Gleisberg, Krauss]
-- for the virtuals in sight
-- process independent matching procedure available and shower indepedent.

* New showers and matching

Several proposals for new shower algorithms where the matching with LO and NLO results should be easier:

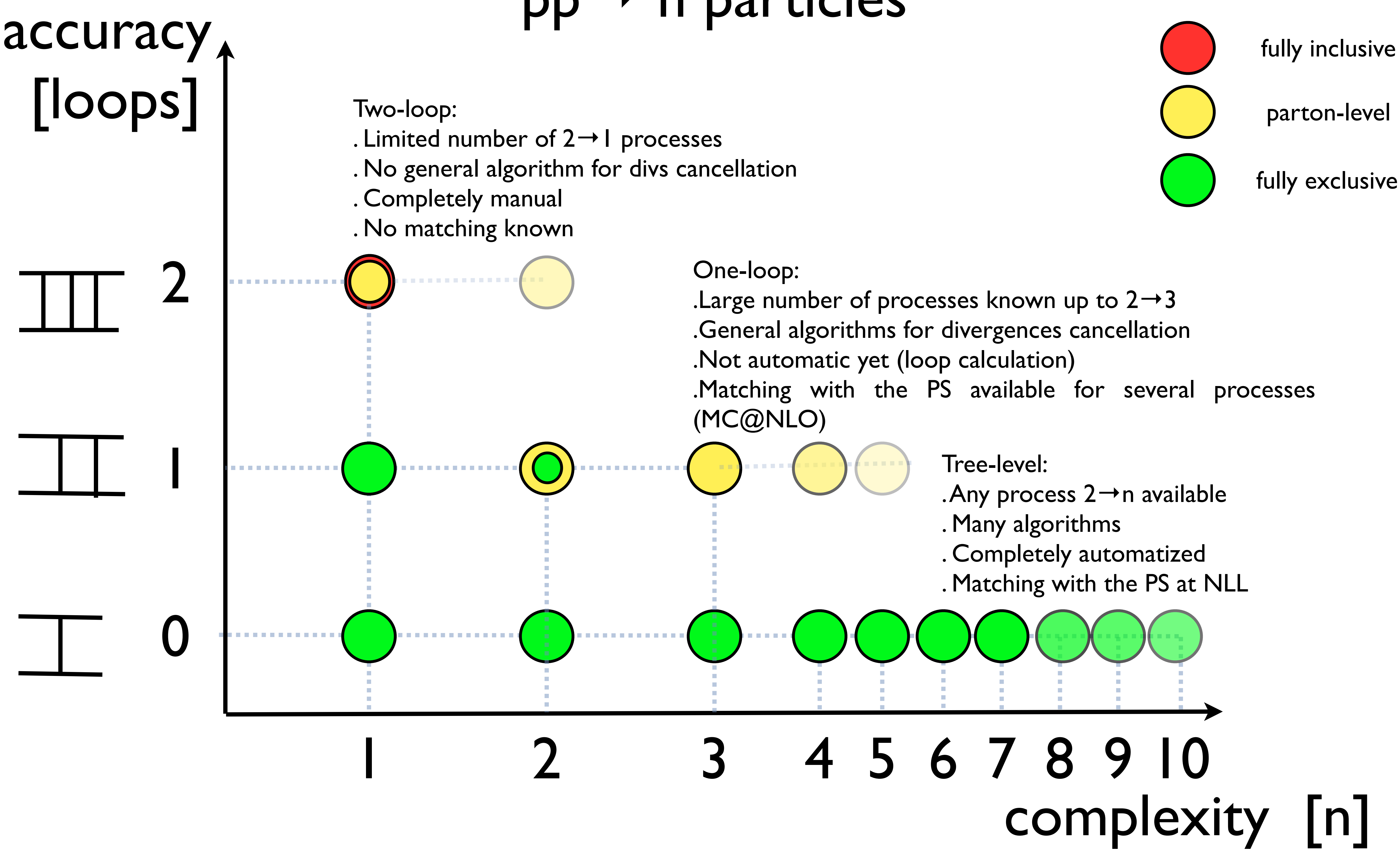
-- Antenna based shower (VINCIA) [Giele, Kosower, Skands]
-- Catani-Seymour dipole shower [Schumann, Krauss; Dinsdale, Ternick, Weinzerl]
-- Quantum-interference shower [Nagy, Soper]
-- Shower based on SCET [Bauer, Schwartz]
-- The GenEva approach [Bauer, Thaler]

* NLO + ME + PS

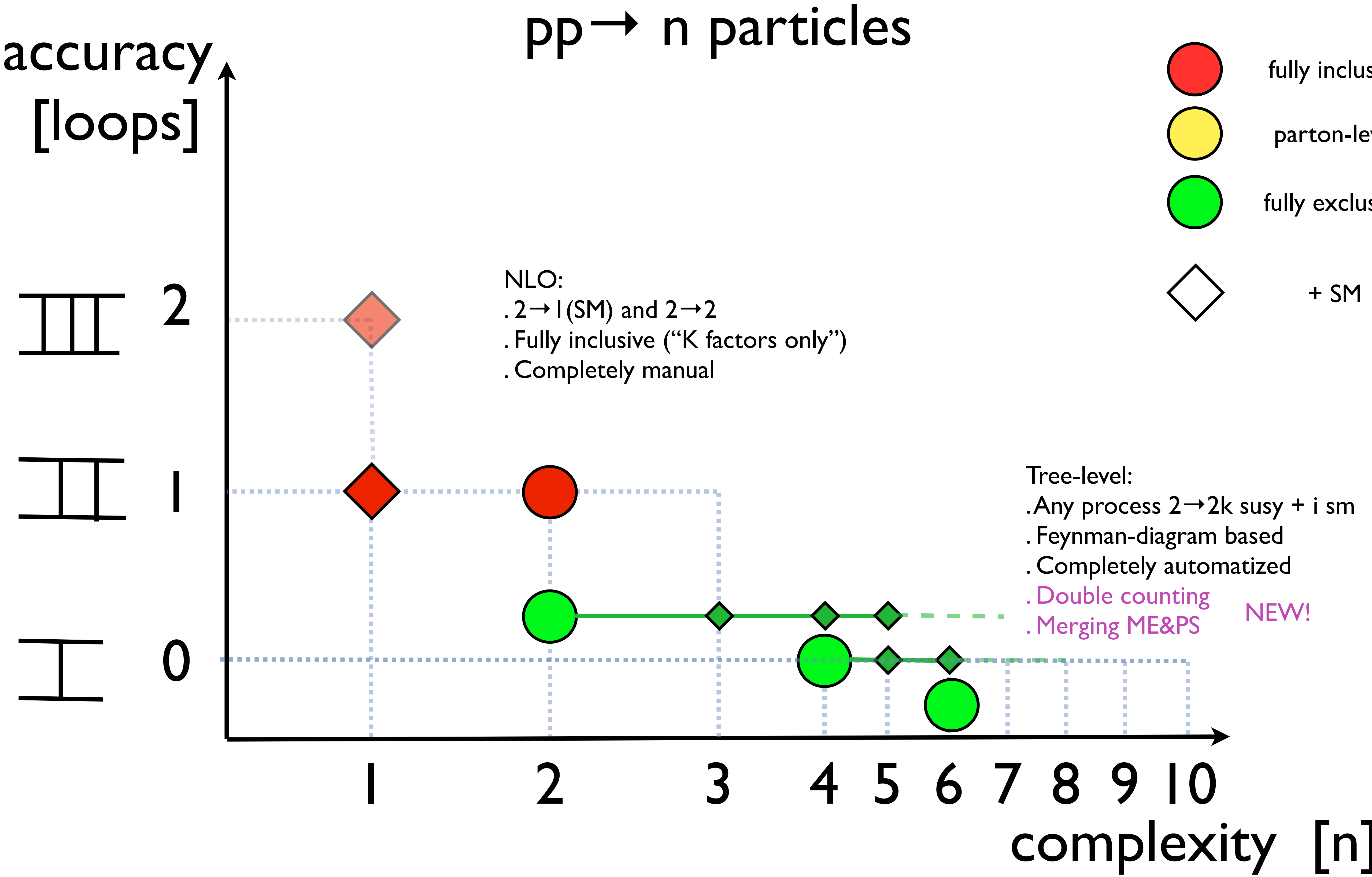


Status

pp→ n particles



Status: SUSY



pp→ n particles
accuracy [loops]
2
1
0
fully inclusive
parton-level
fully exclusive
+ SM
NLO:
. 2→1(SM) and 2→2
. Fully inclusive ("K factors only")
. Completely manual
Tree-level:
. Any process 2→2k susy + i sm
. Feynman-diagram based
. Completely automatized
. Double counting
. Merging ME&PS
NEW!
1 2 3 4 5 6 7 8 9 10
complexity [n]

The perfect jets

The quest for good jets has a long history

Snowmass Accord (1990):

FERMILAB-Conf-90/249-E
[E-741/CDF]

Toward a Standardization of Jet Definitions

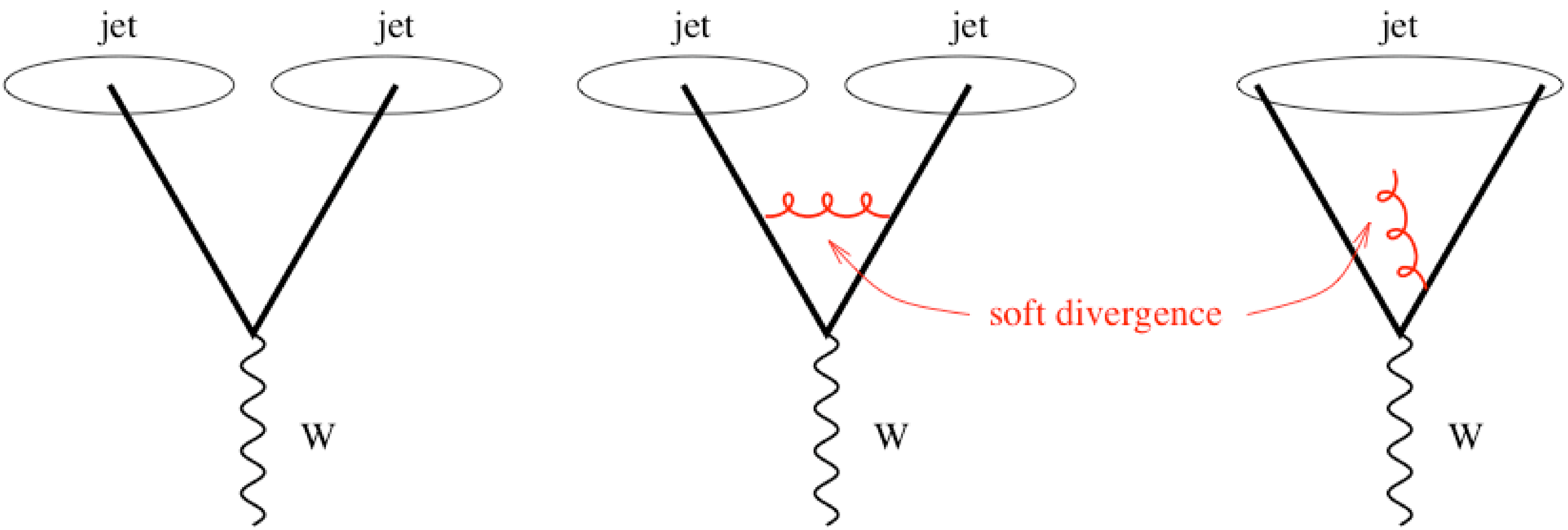
Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

Many attempts in the past to reconcile theory solid definitions with experimental needs.

Result: a plethora of jet algorithms available, a lot of confusion, inconsistent comparisons between TH and EXP data.

Example: JetClu

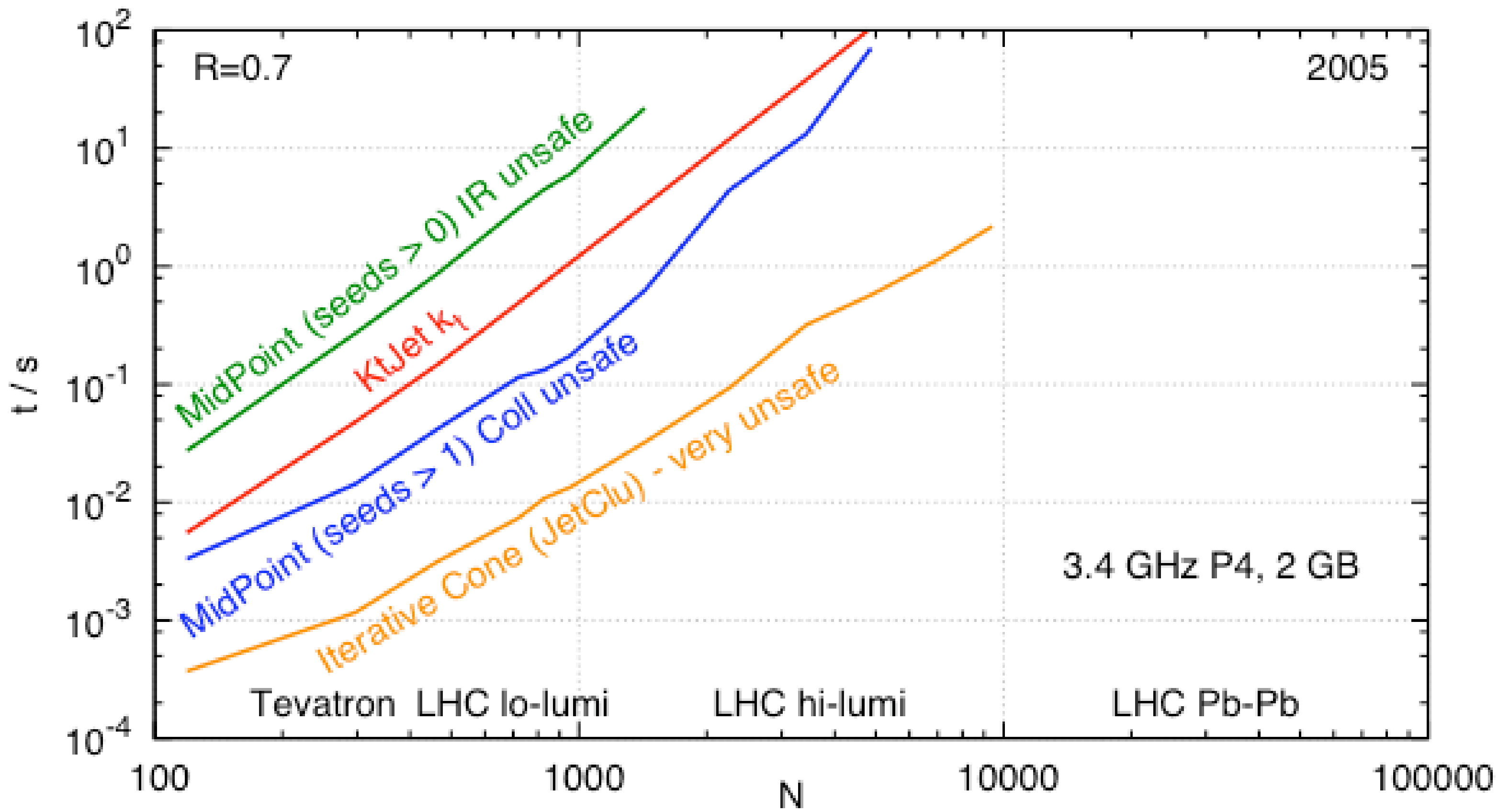


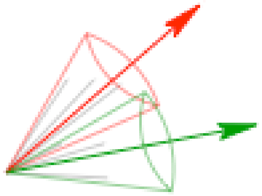
	$\alpha_s^2\alpha_{EW}$	$\alpha_s^3\alpha_{EW}$	$\alpha_s^3\alpha_{EW}$
1-jet			$+\infty$
2-jet	$\mathcal{O}(1)$	$-\infty$	**0**

The algorithm is not infrared safe

Jets : the past

Two approaches:
cone type : cluster particles according to their distance in coordinate space (IR safe in principle, but too slow $O(N2^N)$ and EXP versions are IR unsafe)
sequential type : cluster particles according to their distance in momentum space (IR safe but too slow $O(N^3)$)





Simple idea # 3

[Cacciari, Salam & Soyez]

k_t algorithm

- Find smallest of all $d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2$ and $d_{iB} = k_i^2$
- Recombine i, j (if iB: $i \rightarrow$ jet)
- Repeat

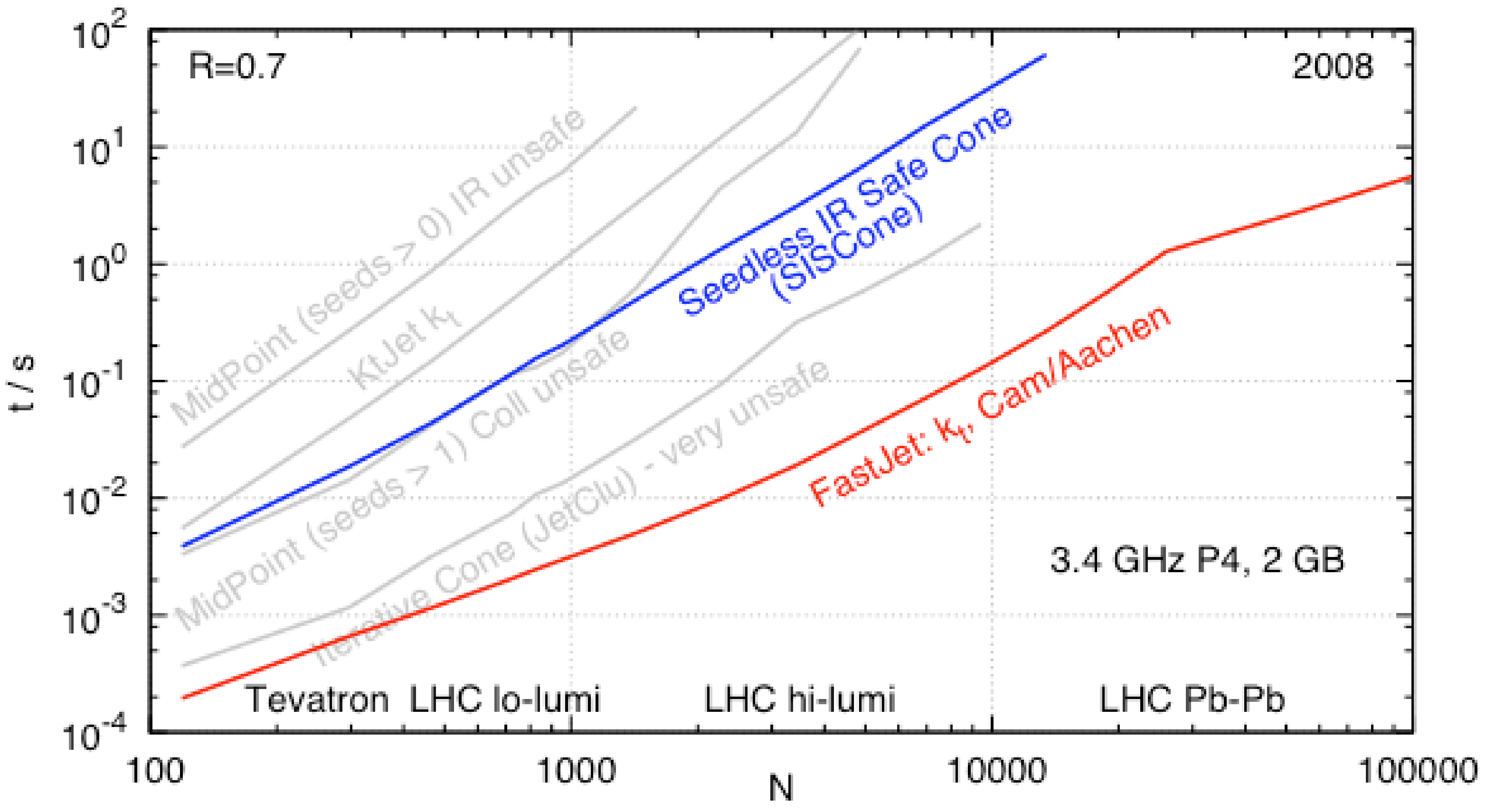
Factorize momentum and geometry. Use methods and tools from computational geometry to reduce the growth from N^3 to N log N.

Similar approach can be applied to several cone- and sequential-type jets can be properly defined and implementend in a fast and IR safe way.

SISCone : N^2 log N and IR safe
kt : N log N
anti-kt : N n

Public implementation, FastJet, available on the web.

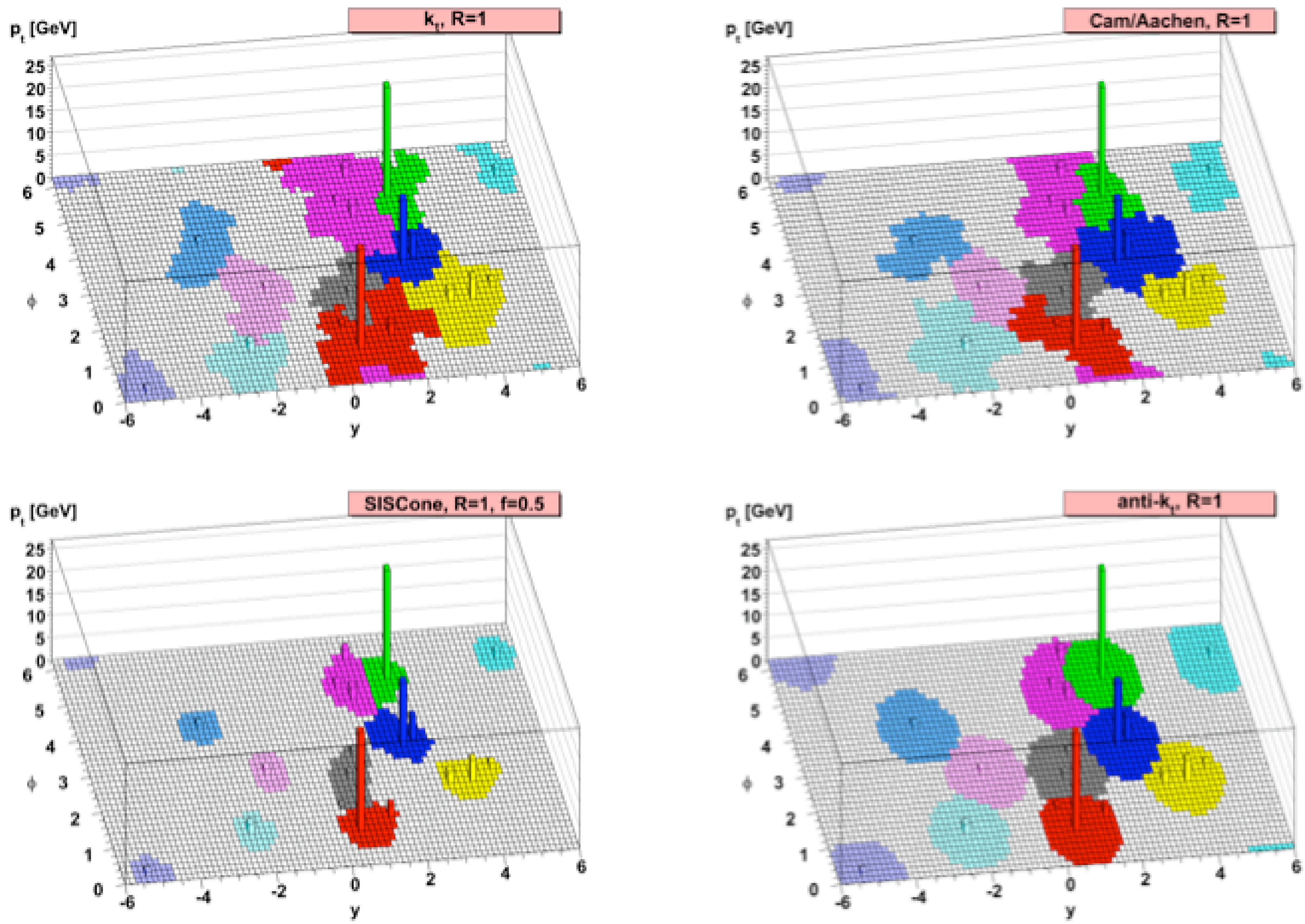
Jets : the present



SISCone as fast as MidPoint but IR-safe

Kt faster than JetClu

Jets : the present



Two new algorithms provide FAST and IR-safe versions with similar characteristics of all the commonly used IR non-safe algorithms!! New studies are possibile : Jet areas, UE subtraction on event-by-event basis, jet structures for boosted particles (Higgs,W,top)

Conclusions

- The need for better description of QCD for the LHC has motivated a significant increase of theoretical and phenomenological activity, leading to several important results.
- As examples, I briefly presented
  - ★ Progress in the automatic computation of one-loop amplitudes appearing in the calculation of QCD corrections of multi-parton processes.
  - ★ Progress in fixed-order and parton-shower matching both at tree-level (Matrix element + PS) and NLO (MC@NLO and POWHEG).
  - ★ New IR-safe and exp friendly jet algorithms.
- Shift in paradigm: useful TH predictions in the form of tools that can be used by EXP's. Communication and collaboration between THs & EXPs easier $\Rightarrow$ emergence of an integrated LHC community.

Take a look around
At all people everywhere
So much energy and excitement in the air
And the time is right
To get together with the people you know
So sing out loud and clear don't be afraid
To let the LHC start

Chorus:

Are you ready for it?
Rockin' steady for it
Are you ready for it?
Rockin' steady for it
Are you ready for it?

Madonna

Credits

Many thanks for providing material, physics insights or both to this talk:

Simon de Visscher, Stefano Frixione, Eric Laenen, Carlo Oleari, Gavin Salam

Preventive apologies for omissions and misquotations.